NASA-CR-200979

Annual Report
Grant No. NAG-1-1180
July 1, 1995 - June 30, 1996

CENTER FOR ADVANCED COMPUTATIONAL TECHNOLOGY

Submitted to:

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National Aeronautics and Space Administration/Headquarters
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SEAS Report No. UVA/528357/CEAM96/101
May 1996

DEPARTMENT OF CIVIL ENGINEERING AND APPLIED MECHANICS

SCHOOL OF
ENGINEERING
& APPLIED SCIENCE

University of Virginia
Thornton Hall
Charlottesville, VA 22903

TABLE OF CONTENTS

ABSTRACT

The Center for Advanced Computational Technology (ACT), formerly the Center for Computational Structures Technology, was established to serve as a focal point for the diverse CST research activities. The CST activities include the use of numerical simulation and artificial intelligence methods in modeling, analysis, sensitivity studies, and optimization of flight vehicle structures. The activities of the Center expanded in 1996 to include other areas of computational technology such as applications of multimedia and synthetic environments, and computational intelligence. The Center is located at NASA Langley and is an integral part of the School of Engineering and Applied Science of the University of Virginia. The Center has the following four specific objectives: 1) to conduct innovative research on applications of advanced computational technology to aerospace systems; 2) to act as pathfinder, by demonstrating to the research community what can be done (high-potential, high-risk research); 3) to help in identifying future directions of research in support of the aeronautical and space missions of the twenty-first century; and 4) to help in the rapid transfer of research results to industry and in broadening awareness among researchers and engineers of the state-of-the-art in applications of advanced computational technology to the analysis, design prototyping and operations of aerospace and other high-performance engineering systems.

In addition to research, the activities of the Center include coordinating the activities of a multicenter team of NASA and JPL researchers who are developing an analysis and design environment for future aerospace systems; organizing workshops and national symposia; as well as writing state-of-the-art monographs and NASA special publications on timely topics.

The Principal Investigator for this Cooperative Agreement is Dr. Ahmed K. Noor, Ferman W. Perry Professor of Aerospace Structures and Applied Mechanics, who is serving as the Director for the Center, and the NASA monitor is Dr. Dana Brewer, NASA Headquarters.

PROPOSED ACTIVITIES

In the coming period (July 1, 1996-June 30, 1997), the activities of the Center will include:

1. Conducting research in the following areas: a) analysis and design environment for future aerospace systems; b) innovative computational strategies for large-scale nonlinear structural problems; c) prediction and analysis of damage and failure of structural components; d) thermomechanical buckling, postbuckling and failure-analysis of composite and sandwich panels and shells; e) high-fidelity modeling of flight vehicle structures; f) design-oriented CST; g) reanalysis strategies for large-scale design optimization; and h) nonlinear structural dynamics for space systems. The research activities will be coordinated with on-going research at NASA Langley, NASA Lewis, JPL, and whenever appropriate, with other NASA Centers. A brief description of each research activity is given in Appendix I.

2. Coordinating the activities of a multicenter team consisting of NASA, JPL researchers, commercial software vendors, industrial firms, and universities on analysis and design environment for future aerospace systems. A brief description of the activity is given in Appendix II.

3. Organizing two to three workshops every year. The workshops to be organized in 1996/1997 are: a) Computational Tools for Future Analysis and Design Environment; and b) Simulation Based Design.

4. Organizing seminar series by leading experts in different areas of ACT at NASA Langley, Lewis, JPL and possibly, other NASA Centers.

5. Holding national symposia and hosting national conferences on timely topics.

6. Writing and editing special publications and monographs on timely topics. The monograph on Future Aeronautical and Space Systems is scheduled for publication in 1996. Another monograph on Computational Technology for Future Flight Vehicles is planned for 1997.

7. Working out collaborative agreements with leading centers in the U.S. in areas which can significantly impact the development of ACT (such as the Center on High-Performance Computing of the University of Minnesota, and the NSF sponsored Institute of Mechanics at the University of California at San Diego). Arrangements will be made to use the resources of these centers in our research projects at no cost to the grant.

FACILITIES

The computational and experimental facilities at NASA Langley Research Center will be used in performing part of this research. Other computational facilities (e.g., at NSF Illinois and San Diego Supercomputer Centers, CRAY Research, and the High-Performance Computing Center at Vicksburg, MS) will be used by a special arrangement with Dr. Ahmed K. Noor at no cost to this cooperative agreement.

SUMMARY OF RECENT PROGRESS

During the last period (July 1, 1995-May 30, 1996), a total of ten research scientists, one senior programmer/analyst, two program support technicians, one executive secretary, and one summer student were supported by the Center. The list of the Center Staff is given in Appendix II. The accomplishments of the Center during this period, under the present cooperative agreement include completing a six-volume monograph; publication of two NASA CP's, 28 journal articles, making five presentations; organizing three seminars; and working cooperative agreements with thirteen commercial software vendors. These accomplishments are listed in Appendices IV through VII and are briefly described subsequently.

1. Conducting research in the following general areas: a) innovative computational strategies for large-scale structural problems; b) prediction and analysis of failure of structural components made of composite materials, and subjected to combined thermal and mechanical loads; c) sensitivity analysis for large structural systems; and d) nonlinear structural dynamics.

A total of twenty-eight research publications and five presentations have been made under the present cooperative agreement during this time period. A list of the publications and presentations are given in Appendix IV. Also, the abstracts of the publications are included in Appendix VII.

2. Organizing a Training Seminar on Computational Intelligence to acquaint NASA researchers and contractors with the technology, and help them adapt it to the analysis and design of future aerospace systems. The seminar speakers included leading experts in the field: Prof. Lotfi A. Zadeh, University of California at Berkeley; Dr. Samuel J. Biondo, U.S. Department of Energy; Prof. Mohammed Jamshidi, University of New Mexico, Albuquerque; Prof. George Vachtsevanos, Georgia Institute of Technology, Atlanta, GA; and Prof. Marian Stachowicz, University of Minnesota, Duluth. The seminar was attended by 64 people (26 NASA, 18 industry (8 NASA contractors), 4 government labs., and 16 university). A complete set of notes was provided to the attendees.

3. Organizing site visits for NASA and JPL researchers and managers to leading centers and companies in the virtual environment area (see Appendix V).

4. Organizing a seminar series by leading experts in the CST and related areas. Two seminars were given at Langley . The list of seminars is given in Appendix V.

5. Completing the six-volume Monograph on "Flight Vehicle Materials, Structures and Dynamics - Assessment and Future Directions."

APPENDICES

I. RESEARCH PROJECTS

II. NEXT GENERATION ANALYSIS AND DESIGN ENVIRONMENT FOR AEROSPACE SYSTEMS

III. CENTER STAFF

IV. LIST OF PUBLICATIONS AND PRESENTATIONS

V. LIST OF SEMINARS AND SITE VISITS

VI. COOPERATING ORGANIZATIONS

VII. ABSTRACTS OF PUBLICATIONS

Appendix I

Research Projects

Analysis and Design Environment for Future Aerospace Systems. A distributed, collaborative virtual analysis/design environment is being developed for radically advancing the process by which complex aerospace systems are designed, manufactured and operated. The environment will be used for simulating the entire life cycle of aerospace systems from concept development, detailed design, and prototyping to qualification testing, operations and disposal. It will incorporate the state-of-the-art computational, communication and synthetic environment facilities and tools. The environment will be highly interactive and capable of dynamically mapping information into visual, auditory or kinesthetic representations. It will include computational intelligence modules (fuzzy logic, evolutionary strategies and neural networks), and the infrastructure for collaborative computing among geographically dispersed teams. The computational tools in the environment cover the entire life cycle of the aerospace system and include high-fidelity rapid modeling facilities, and physics-based simulation tools for structures, dynamics, controls, optics, thermal management, power and propulsion. They also include tools for mission design, cost modeling and estimating; product assurance, safety analysis and risk management; as well as tools for simulation of prototyping, testing for qualifications and operations. The environment will help in assessing the manufacturability and in the rapid insertion of new product technology. It will significantly shorten the design and development times of future aerospace systems, reduce their life-cycle cost, and improve their performance.

Innovative Computational Strategies for Large-Scale Structural and Coupled Problems. The scope of this research covers transient thermal and dynamic problems, nonlinear static problems, and postbuckling problems. The three major activities are:

• *Hierarchical adaptive modeling strategies* for simulating response phenomena occurring at disparate spatial and time scales, using reasonable computer resources. The strategies use multiple mathematical models in different regions of the structure to take advantage of efficiencies gained by matching the model to the expected response in each region. Adaptivity in the strategy minimizes reliance on *a priori* assumptions about the response. An object-oriented interactive environment is being developed which not only allows the use of different numerical algorithms in different parts of the structure, but allows the algorithms to be changed dynamically during computation.

• *Strategies for the effective use of diverse high-performance computing platforms.* The platforms considered include supercomputers such as the Cray 916 and Cray 3, massively parallel systems, and other scalable MIMD platforms such as the Intel Paragon XP/S, Cray T3D and IBM SP2. General guidelines are produced for designing future large-scale structural analysis programs that will run efficiently on distributed heterogeneous computing platforms or on hardware tailored for structural calculations.

• *Effective hybrid strategies*, including numerical/analytical and numerical/neurocomputing methods.

Prediction and Analysis of Damage and Failure of Structural Components. Practical numerical simulation techniques are sought for predicting the failure initiation and propagation in structural components, especially those made of new high-performance materials in terms of measurable and controllable parameters. Examples of these materials are high-temperature materials for hypersonic vehicles; piezoelectric composites; electronic, optical, and smart materials for space applications. For some of the materials, accurate constitutive descriptions, failure criteria, and damage theories are needed, along with more realistic characterization of interface phenomena (such as contact and friction). The constitutive descriptions may require investigations at the microstructure level or even the atomic level; as well as carefully designed and conducted experiments. Current work at the Center focuses on: a) *development of computational models and effective strategies* for simulating the dynamic failure and damage of metallic structures, and evaluating the sensitivity of failure initiation and propagation to variations in both the microstructure and macrostructure material parameters. An elastic-viscoplastic material model is used, with a temperature-dependent flow strength. The model incorporates thermal softening due to adiabatic heating, and ductile failure by void nucleation. b) *identification of structural response quantities which can be used in predicting failure initiation and propagation* in new materials; and c) *effective coupling between numerical simulations and experiments* to understand the physical phenomena associated with material-level damage, damage growth, and the subsequent structural failure.

Thermomechanical Buckling, Postbuckling and Failure Analysis of Composite and Sandwich Panels and Shells. This area includes the study of buckling and postbuckling responses as well as failure characteristics of laminated composite and sandwich panels subjected to combined thermal and mechanical loads. Both stiffened and unstiffened, flat and curved panels, as well as panels and shells with cutouts are considered. Current work is focused on understanding the thermomechanical response and studying the role of transverse stresses in the failure of composite panels and shells. The overall objective of this research is to develop a verifiable failure analysis capability for fibrous composite and sandwich panels and shells subjected to various loading conditions.

High-Fidelity Modeling of Flight Vehicle Structures. One of the most important steps for the accurate prediction of the response of a complex aerospace structure is the proper selection and sequencing of mathematical and discrete models, with varying degrees of complexity. Hence, there is a need for the development of automatic model generation facilities as well as smart interfaces to the analysis and design systems. The smart interfaces will be AI-based expert systems which run on workstations, can help the engineer in the initial selection of the model, its adaptive refinement, selection of the solution procedure, constraint representation, and the interpretation of results. The work at the Center focuses on identification of modeling details (e.g., computational material models, modeling of joints and damping) needed for accurate description of the response of the structure.

Design-Oriented CST. The realization of new complex aerospace vehicles (e.g., hypersonic vehicles and control-configured aircraft and spacecraft) requires high levels of integration between the structures discipline and other traditionally separate disciplines such as aerodynamics, heat transfer, propulsion, controls, and electromagnetics. This is because of the significant interdisciplinary interactions and couplings, and the need to account for these couplings in predicting the response, as well as for the optimum design of these vehicles.

New methodologies are needed for integrated design and optimization of aerospace vehicles in the presence of strong interdisciplinary couplings. Work at the Center focuses on: a) development of sensitivity and computational intelligence methods for large-scale problems; and b) effective approaches for linking of CST to other disciplines through modular integration and/or simultaneous treatment of the different disciplines (at the governing equations level).

Reanalysis Strategies for Large-Scale Design Optimization. Effective reanalysis strategies are being developed for use in the optimum design of large structural components (with large numbers of degrees of freedom, loading cases, design variables, and constraints). Current work focuses on use of multilevel substructuring; lumping of design variables into tracing parameters which identify the effect of structural modifications on individual substructures; and application of operator splitting/reduction technique to generate the response of the modified structure as a large perturbation from that of the original structure. Quantitative measures for the sensitivity of the response quantities to modifications of the individual substructures are generated as an integral part of the proposed strategy. The strategy is being applied to both static, free vibration, nonlinear and dynamic problems.

Nonlinear Structural Dynamics for Space Systems. The tasks included in this research are: a) development of efficient computational strategies for predicting the transient response and internal loads of large spacecraft subjected to impact loads (e.g., docking forces), simulating the response of articulated dynamical systems, and evaluating the sensitivity of the dynamic response of large actively controlled spacecraft to variations in geometric and material parameters, as well as to actuator/sensor locations; and b) development of model reduction techniques for use in control/structural interaction problems of large spacecraft. The articulated dynamical systems considered are flexible multibody systems which include deployable space structures, space robots and manipulators. An attempt is made to exploit the major characteristics of high-performance computers in the strategies developed.

Appendix II

Next Generation Analysis and Design Environment for Aerospace Systems

1. Overall Goal

The overall goal of the activity is to build/assemble an advanced analysis/design environment for aerospace systems which incorporate the state-of-technology computational and communication facilities and tools. The environment is expected to radically advance the process by which complex aerospace systems are designed, manufactured and operated. It will significantly shorten the design and development times of future aerospace systems, reduce their life-cycle cost, and improve their performance.

2. Scope of the Activity

The aerospace systems included in the activity are: new millennium spacecraft, space transportation systems, and high-speed aircraft. The design environment will include generic modules and facilities which are used for all systems, and application-specific tools for individual systems.

3. Major Components

The following four major components of the environment have been identified:

- Distributed immersive environment
- Infrastructure for collaborative computing
- Rapid computational tools and modeling methods
- System integration tools and databases

The four components are described subsequently.

3.1 *Immersive Environment and Human-Computer Interfaces*

The objective of this component is to increase the productivity of the design/ manufacturing team by significantly enhancing the communication bandwidth between researchers/designers and machines. The environment will be highly interactive and capable of dynamically mapping information into visual, auditory or kinesthetic representations.

The state-of-the-technology facilities (e.g., MUSE of MUSE Tech and the CAVE at the University of Illinois) will be used through collaborative arrangements with the developers of these facilities.

An attempt will be made to identify the promising interaction paradigms and techniques which allow the researchers/engineers to see, hear, touch and interact with product models. However, traditional access mechanisms based on flat screen displays will be supported.

3.2 *Infrastructure for Collaborative Computing*

This component will provide a multimedia environment for enabling collaborative design and integrated product viewing among geographically dispersed teams (e.g., Langley, JPL, Goddard, ...). Initially, NASA ATM network will be used in conjunction with commercial and public domain software. A multiperspective approach to collaborative design will be supported.

3.3 *Rapid Computational Tools and Modeling Methods*

The computational tools cover the entire life cycle of the aerospace system. They include high-fidelity, rapid modeling facilities, and physics-based simulation tools for structures, dynamics, controls, thermal management, power, propulsion. They also include tools for mission design, cost modeling and estimating; product assurance, safety analysis and risk management; as well as tools for simulation of prototyping, testing for qualifications and operations.

All the aforementioned tools will account for uncertainties through the use of probabilistic and fuzzy-logic based techniques. An attempt will be made to use the best available among the in-house and commercial tools for performing each task.

3.4 *System Integration Tools and Databases*

This component will use object-oriented technology to facilitate the linking of different modules and tools of the environment. It will enable the rapid, easy access and sharing of information among design teams. The component will allow concurrent activities among physically distributed data sets, analysis codes and organizations. It will include tools for data retrieval and translation; intelligent dispatchers for selecting the correct tool for the job; intelligent design agents for automating semi-routine design tasks. The system will maintain the constantly evolving nature of aerospace system information, and the many different perspectives which different individuals may have for that information at any given time (i.e., multiple concurrent object representations, or views are supported on demand).

Appendix III - Center Staff

A. Research Scientists

1. Burton, W. Scott (Ph.D.), Carnegie-Mellon Univ., Pittsburgh, PA (appointed Aug. 1, 1990).
2. Kim, Yong H. (Ph.D.), University of Maryland, College Park (appointed July 15, 1991; terminated Sept. 6, 1995).
3. Karaoglan, Levent (Ph.D.), Stanford University, Stanford, CA (appointed Oct. 19, 1992).
4. Danielson, Kent T. (Ph.D.), Texas A&M University, College Station, TX (appointed June 14, 1993; terminated May 31, 1996).
5. Watson, Brian C. (Ph.D.), Georgia Institute of Technology, Atlanta, GA (appointed July 6, 1993; terminated February 29, 1996).
6. Pollock, Gerry D. (Ph.D.), Univ. of Illinois at Urbana-Champaign (appointed Aug. 2, 1993; terminated March 18, 1996).
7. Szewczyk, Z. Peter (Ph.D.), Rensselaer Polytechnic Institute, Troy, NY (appointed July 19, 1993).
8. Xu, Kangming (Ph.D.), Northwestern University, Evanston, IL (appointed Jan. 3, 1994).
9. Wasfy, Tamer D. (Ph.D.), Columbia University, New York, NY (appointed March 13, 1995)

B. Supporting Staff

1. Jeanne M. Peters, Senior Programmer Analyst (appointed July 1, 1990).
2. Catherine M. Richter, Program Support Technician (appointed June 21, 1993).
3. Cynthia H. Brown, Part-time Program Support Technician (appointed Feb. 23, 1996).
4. Mary L. Torian, Executive Secretary (appointed July 1, 1990)
5. Justin Neil Lapierre, summer Student (appointed June 1, 1995; terminated Aug. 26, 1995)

Appendix IV - Publications and Presentations

A. <u>Publications</u>

1. Kulkarni, M. and Noor, A. K., "Sensitivity Analysis of the Nonlinear Dynamic Viscoplastic Response of Two-Dimensional Structures with Respect to Material Parameters," *International Journal for Numerical Methods in Engineering*, Vol. 38, No. 2, 1995, pp. 183-198.

2. Noor, A. K., "UVA Center for Computational Structures Technology," *IEEE Computational Science and Technology*, Vol. 2, No. 4, 1995, pp. 10-14.

3. Xu, K., Noor, A. K. and Tang, Y. Y., "Three-Dimensional Solutions for Coupled Thermoelectroelastic Response of Multilayered Plates," *Computer Methods in Applied Mechanics and Engineering*, Vol. 126, Nos. 3-4, Oct. 1995, pp. 355-371.

4. Karaoglan, L. and Noor, A. K., "Dynamic Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures," *Computer Methods in Applied Mechanics and Engineering*, Vol. 128, Nos. 1-2, 1995, pp. 169-190

5. Noor, A. K., Starnes, J. H., Jr. and Peters, J. M., "Thermomechanical Postbuckling of Multilayered Composite Panels with Cutouts,"*Composite Structures*, Vol. 30, No. 4, 1995, pp. 369-388.

6. Watson, B. C. and Noor, A. K., "Nonlinear Structural Analysis on Distributed-Memory Computers," *Computers and Structures*, Vol. 58, No. 2, Jan. 1996, pp. 233-248.

7. Szewczyk, Z. P. and Noor, A. K., "A Hybrid Neurocomputing/Numerical Strategy for Nonlinear Structural Analysis," *Computers and Structures*, Vol. 58, No. 4, Feb. 1996, pp. 661-678

8. Noor, A. K., Burton, W. S. and Bert, C., "Computational Models for Sandwich Panels and Shells," *Applied Mechanics Reviews*, ASME, Vol. 49, No. 3, March 1996, pp. 155-199.

9. Noor, A. K., "Recent Advances in the Sensitivity Analysis for the Thermomechanical Postbuckling of Composite Panels," in *Aerospace Thermal Structures and Materials for a New Era*, E. A. Thornton (ed.), AIAA Series *Progress in Astronautics and Aeronautics*, Vol. 168, 1995, pp. 218-239; also ASCE *Journal of Engineering Mechanics*, Vol. 122, No. 4, April 1996, pp. 300-307.

10. Xu, K. and Noor, A. K., "Three-Dimensional Analytical Solutions for Coupled Thermoelectroelastic Response of Multilayered Cylindrical Shells," *AIAA Journal*, Vol. 34, No. 4, April 1996, pp. 802-812.

11. Kulkarni, M. and Noor, A. K., "Sensitivity Analysis for the Dynamic Response of Thermoviscoplastic Shells of Revolution," *Computer Methods in Applied Mechanics and Engineering*, Vol. 129, 1996, pp. 371-391.

12. Watson, B. C. and Noor, A. K., "Sensitivity Analysis for Large-Deflection and Postbuckling Responses on Distributed-Memory Computers," *Computer Methods in Applied Mechanics and Engineering*, Vol. 129, 1996, pp. 393-409.

13. Danielson, K. T., Noor, A. K. and Green, J. S., "Computational Strategies for Tire Modeling and Analysis," *Computers and Structures* (to appear).

14. Danielson, K. T. and Noor, A. K., "Finite Elements Developed in Cylindrical Coordinates for Three-Dimensional Tire Analysis," *Tire Science and Technology* (to appear).

15. Karaoglan, L., Noor, A. K. and Kim, Y. H., "Frictional Contact/Impact Response of Textile Composite Structures," *Composite Structures* (to appear).

16. Karaoglan, L. and Noor, A. K., "Assessment of Temporal Integration Schemes for the Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures," *Computer Methods in Applied Mechanics and Engineering* (to appear).

17. Kim, Y. H. and Noor, A. K., "Buckling and Postbuckling of Composite Panels with Cutouts Subjected to Combined Loads," *Finite Elements in Analysis and Design* (to appear).

18. Noor, A. K. and Kim, Y. H., "Buckling and Postbuckling of Composite Panels with Cutouts Subjected to Combined Edge Shear and Temperature Change," *Computers and Structures* (to appear).

19. Noor, A. K. and Peters, J. M., "Reduction Technique for Tire Contact Problems," in NASA CP-3306, pp. 69-88; also *Computers and Structures* (to appear).

20. Noor, A. K. and Peters, J. M., "Nonlinear and Postbuckling Analyses of Curved Composite Panels Subjected to Combined Temperature Change and Edge Shear," *Computers and Structures* (to appear).

21. Pollock, G. D. and Noor, A. K., "Sensitivity Analysis of the Contact/Impact Response of Composite Structures," *Computers and Structures* (to appear).

22. Szewczyk, Z. P. and Noor, A. K., "A Hybrid Numerical/Neurocomputing Strategy for Sensitivity Analysis of Nonlinear Structures," *Computers and Structures* (to appear).

23. Tang, Y. Y., Noor, A. K. and Xu, K., "Assessment of Computational Models for Thermoelectroelastic Multilayered Plates," *Computers and Structures* (to appear).

24. Wasfy, T. M., "Modeling and Sensitivity Analysis of Multibody Systems Using New Solid, Shell and Beam Elements," *Computer Methods in Applied Mechanics and Engineering* (to appear).

25. Watson, B. C. and Noor, A. K., "Sensitivity Analysis of Frictional Contact/Impact Response on Distributed-Memory Computers," *Computers and Structures* (to appear).

26. Watson, B. C. and Noor, A. K., "Large-Scale Contact/Impact Simulation and Sensitivity Analysis on Distributed-Memory Computers," *Computer Methods in Applied Mechanics and Engineering* (to appear).

27. Xu, K., Noor, A. K. and Burton, W. S., "Three-Dimensional Solutions for Free Vibrations of Initially-Stressed Thermoelectroelastic Multilayered Cylinders," *Journal of Engineering Mechanics* (to appear).

28. Xu, K., Noor, A. K. and Tang, Y. Y., "Three-Dimensional Solutions for Free Vibrations of Initially-Stressed Thermoelectroelastic Multilayered Plates," *Computer Methods in Applied Mechanics and Engineering* (to appear).

B. Presentations

1. Noor, A. K., "Sensitivity Analysis for Large-Deflection and Postbuckling Responses on Distributed-Memory Computers," International Conference on Computational Engineering Science, Hawaii, July 30-Aug. 3, 1995.

2. Noor, A. K., "Three-Dimensional Solutions for Free Vibrations of Initially-Stressed Thermoelectroelastic Multilayered Plates," Symposium on Recent Advances in Engineering Sciences, 32nd Annual Technical Meeting of Society of Engineering Science, New Orleans, LA, Oct. 29-Nov. 1, 1995.

3. Noor, A. K., "Thermomechanical Buckling and Postbuckling Responses for Composite Panels with Skewed Stiffeners," 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Salt Lake City, UT, April 15-17, 1996.

4. Noor, A. K., "Sensitivity Analysis of Frictional Contact/Impact Response on Distributed-Memory Computers," (invited talk), Workshop on Recent Advances in Computational Structural Dynamics and High-Performance Computing, USAE Waterways Experiment Station, Vicksburg, MS, April 24-26, 1996.

5. Noor, A. K., AFOSR 1996 Contractors Workshop in Structural Mechanics, Virginia Beach, VA, June 25-27, 1996.

Appendix V - Seminars and Site Visits

A. <u>Training Seminars</u>
   1. Computational Intelligence, Mar. 6-7, 1996

B. <u>Seminars</u>
   1. Slobodan Sipcic, "Application of Mathematica to Education and Research in Mechanics, " Feb. 12, 1996
   2. Gary Jones and Sam Nicholson, DARPA Program on SBD, Feb. 22, 1996
   3. Vladimir V. Bolotin, "Fatigue and Fracture of Metals and Elastomers," Mar. 15, 1996
   4. CAI, Inc., "Multimedia Presentation and Demonstration of Cactis MultiPro," May 7, 1996

C. <u>Site Visits</u>
   1. IBM Multimedia Center, Atlanta, GA, Oct. 17, 1995
   2. MUSE Technologies, Inc., Albuquerque, NM, January 16-17, 1996
   2. Electronic Visualization Laboratory, University of Illinois at Chicago, Chicago, IL, April 8, 1996
   3. EDS Detroit Virtual Reality Center, Detroit, MI, April 9, 1996.
   4. Scientific Research Lab., Ford Motor Company, Detroit, MI, April 9, 1996.

Appendix VI - Cooperating Organizations

1. The MacNeal-Schwendler Corp.
   815 Colorado Blvd.
   Los Angeles, CA 90041

2. ANSYS, Inc.
   Johnson Road
   P.O. Box 65
   Houston, PA 15342

3. Hibbitt, Karlsson & Sorensen, Inc.
   1080 Main Street
   Pawtucket, RI 02860

4. Centric Engineering Systems, Inc.
   3801 East Bayshore Road
   Palo Alto, CA 94303

5. ADINA R&D, Inc.
   71 Elton Avenue
   Watertown, MA 02172

6. Superscape, Inc.
   2479 East Bayshore #706
   Palo Alto, CA 94303

7. CEI, Inc.
   P.O. Box 14306
   Research Triangle Park, NC 27709

8. IBM
   321 West Rio Road
   Charlottesville, VA 22901

9. Center for Educational Computing Initiatives
   Massachusetts Inst. of Technology
   Cambridge, MA 02139

10. Wolfram Research, Inc.
    100 Trade Center Drive
    Champaign, IL 61820

11. UniSQL, Inc.
    2111 Wilson Blvd., 7th Floor
    Arlington, VA 22201

12. Macsyma, Inc.
    20 Academy Street
    Arlington, MA 02174

13. CAI Consulting Associates, Inc.
    Greenbrier Circle Corporate Center
    825 Greenbrier Circle, Suite 205
    Chesapeake, VA 23320

Appendix VII - Abstracts of Publications

Sensitivity Analysis of the Nonlinear Dynamic Viscoplastic Response of Two-Dimensional Structures with Respect to Material Parameters

Makarand Kulkarni and Ahmed K. Noor

A computational procedure is presented for evaluating the sensitivity coefficients of the viscoplastic response of structures subjected to dynamic loading. A state of plane stress is assumed to exist in the structure, a velocity strain-Cauchy stress formulation is used, and the geometric nonlinearities arising from large strains are incorporated. The Jaumann rate is used as a frame indifferent stress rate. The material model is chosen to be isothermal viscoplasticity, and an associated flow rule is used with a von-Mises effective stress. The equations of motion emanating from a finite element semi-discretization are integrated using an explicit central difference scheme with an implicit stress-update. The sensitivity coefficients are evaluated using a direct differentiation approach. Since the domain of integration is the current configuration, the sensitivity coefficients of the spatial derivatives of the shape functions must be included. Numerical results are presented for a thin plate with a central circular cutout subjected to an in-plane compressive loading. The sensitivity coefficients are generated by evaluating the derivatives of the response quantities with respect to Young's modulus, and two of the material parameters characterizing the viscoplastic response. Time histories of the response and sensitivity coefficients, and spatial distributions at selected times are presented.

International Journal for Numerical Methods in Engineering, Vol. 38, No. 2, 1995, pp. 183-198.

UVA Center for Computational Structures Technology

Ahmed K. Noor

Recognizing the importance of computation in developing man-made structures generally, and particularly in the multidisciplinary design of complex flight vehicles, NASA and the University of Virginia established a Center for Computational Structures Technology in July 1990. An integral part of UVA's School of Engineering and Applied Science, the UVA-CST Center is located at NASA Langley Research Center in Hampton, Virginia. It is also affiliated with the Virginia Consortium of Engineering and Science Universities, established in 1994 to focus on graduate education.

IEEE Computational Science and Technology, Vol. 2, No. 4, 1995, pp. 10-14.

Three-Dimensional Solutions for Coupled Thermoelectroelastic Response of Multilayered Plates

Kangming Xu, Ahmed K. Noor and Yvette Y. Tang

Analytic three-dimensional solutions are presented for the coupled thermoelectroelastic response of multilayered hybrid composite plates. The plates consist of a combination of fiber-reinforced cross-ply and piezothermoelastic layers. Both the thermoelectroelastic static response and its sensitivity coefficients are computed. The sensitivity coefficients measure the sensitivity of the response to variations in different mechanical, thermal and piezoelectric material properties of the plate. A linear constitutive model is used, and the material properties are assumed to be independent of the temperature and the electric field. The plates are assumed to have rectangular geometry and special material symmetries.

A mixed formulation is used with the fundamental unknowns consisting of the three transverse stress components, three displacement components, transverse component of the electric displacement field, electric potential, transverse heat flux component and temperature change. Each of the fundamental unknowns is expressed in terms of a double Fourier series in the Cartesian surface coordinates. A state space approach is used to generate the static response and to evaluate the sensitivity coefficients. Extensive numerical results are presented showing the effects of variation in the geometric parameters of the plate on the different response quantities and their sensitivity coefficients.
Computer Methods in Applied Mechanics and Engineering, Vol. 126, Nos. 3-4, Oct. 1995, pp. 355-371.

Dynamic Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures
L. Karaoglan and A. K. Noor

A computational procedure is presented for evaluating the sensitivity coefficients of the frictional contact/impact response of axisymmetric composite structures. The structures are assumed to consist of an arbitrary number of perfectly bonded homogeneous anisotropic layers. The material of each layer is assumed to be hyperelastic, and the effect of geometric nonlinearity is included. The sensitivity coefficients measure the sensitivity of the response to variations in different material, lamination and geometric parameters of the structure. A displacement finite element model is used for the spatial discretization. The normal contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with the fundamental unknowns consisting of nodal displacements, and Lagrange multipliers associated with the contact conditions. The Lagrange multipliers are allowed to be discontinuous at interelement boundaries. Tangential contact conditions are incorporated by using a penalty method in conjunction with the classical Coulomb's friction model. The temporal integration is performed by using Newmark's scheme. The Newton-Raphson iterative scheme is used for the solution of the resulting nonlinear algebraic equations, and for the determination of the contact region, contact conditions (sliding or sticking), and the contact pressures. The sensitivity coefficients are evaluated by using a direct differentiation approach. Numerical results are presented for the frictional contact/impact response of a composite spherical cap impacting on a rigid plate.
Computer Methods in Applied Mechanics and Engineering, Vol. 128, Nos. 1-2, 1995, pp. 169-190.

Thermomechanical Postbuckling of Multilayered Composite Panels with Cutouts
Ahmed K. Noor, James H. Starnes, Jr. and Jeanne M. Peters

The results of a study of the detailed thermomechanical postbuckling response characteristics of flat unstiffened composite panels with central circular cutouts are presented. The panels are subjected to combined temperature changes and applied edge loading (or edge displacements). The analysis is based on a first-order shear deformation plate theory. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the plate. The postbuckling displacements, transverse shear stresses, transverse shear strain energy density, and their sensitivity coefficients are evaluated. The sensitivity coefficients measure the sensitivity of the postbuckling response to variations in the different lamination and material parameters of the panel. Numerical results are presented showing the effects of the variations in the hole diameter, laminate stacking sequence, fiber orientation, and aspect ratio of the panel on

the thermomechanical postbuckling response and its sensitivity to changes in panel parameters.
Composite Structures, Vol. 30, No. 4, 1995, pp. 369-388.

Nonlinear Structural Analysis on Distributed-Memory Computers
Brian C. Watson and Ahmed K. Noor

A computational strategy is presented for the nonlinear static and postbuckling analyses of large complex structures on massively parallel computers. The strategy is designed for distributed-memory, message-passing parallel computer systems. The key elements of the proposed strategy are: a) a multiple-parameter reduced basis technique; b) a nested dissection (or multilevel substructuring) ordering scheme; c) parallel assembly of global matrices; and d) a parallel sparse equation solver. The effectiveness of the strategy is assessed by applying it to thermo-mechanical postbuckling analyses of stiffened composite panels with cutouts, and nonlinear large-deflection analyses of HSCT models on Intel Paragon XP/S computers. The numerical studies presented demonstrate the advantages of nested dissection-based solvers over traditional skyline-based solvers on distributed memory machines.
Computers and Structures, Vol. 58, No. 2, Jan. 1996, pp. 233-248.

A Hybrid Neurocomputing/Numerical Strategy for Nonlinear Structural Analysis
Z. Peter Szewczyk and Ahmed K. Noor

A hybrid neurocomputing/numerical strategy is presented for geometrically nonlinear analysis of structures. The strategy combines model-free data processing capabilities of computational neural networks with a Pade' approximants-based perturbation technique to predict partial information about the nonlinear response of structures. In the hybrid strategy, multilayer feedforward neural networks are used to extend the validity of solutions by using training samples produced by Pade' approximations to the Taylor series expansion of the response function. The range of validity of the training samples is taken to be the radius of convergence of Pade' approximants and is estimated by setting a tolerance on the diverging approximants. The norm of a residual vector of unbalanced forces in a given element is used as a measure to assess the quality of network predictions. To further increase the accuracy and the range of network predictions, additional training data are generated by either applying linear regression to weight matrices or expanding the training data by using predicted coefficients in a Taylor series. The effectiveness of the hybrid strategy is assessed by performing large-deflection analysis of a double-curved composite panel with a circular cutout, and postbuckling analyses of stiffened composite panels subjected to an in-plane edge shear load. In all the problems considered, the hybrid strategy is used to predict selective information about the structural response, namely the total strain energy and the maximum displacement components only.
Computers and Structures, Vol. 58, No. 4, Feb. 1996, pp. 661-678.

Computational Models for Sandwich Panels and Shells
Ahmed K. Noor, W. Scott Burton and C. W. Bert

The focus of this review is on the hierarchy of computational models for sandwich plates and shells, predictor-corrector procedures, and the sensitivity of the sandwich response to variations in the different geometric and material parameters. The literature reviewed is devoted to the following application areas: heat transfer problems; thermal and mechanical

stresses (including boundary layer and edge stresses); free vibrations and damping; transient dynamic response; bifurcation buckling, local buckling, face-sheet wrinkling and core crimping; large deflection and postbuckling problems; effects of discontinuities (e.g., cutouts and stiffeners), and geometric changes (e.g., tapered thickness); damage and failure of sandwich structures; experimental studies; optimization and design studies. Over 800 relevant references are cited in this review and another 559 references are included in a supplemental bibliography for completeness. Extensive numerical results are presented for thermally stressed sandwich panels and composite face sheets showing the effects of variation in their geometric and material parameters on the accuracy of the free vibration response, and the sensitivity coefficients predicted by eight different modeling approaches (based on two-dimensional theories). The standard of comparison is taken to be the analytic three-dimensional thermoelasticity solutions. Some future directions for research on the modeling of sandwich plates and shells are outlined.
Applied Mechanics Reviews, ASME, Vol. 49, No. 3, March 1996, pp. 155-199.

Recent Advances in the Sensitivity Analysis for the Thermomechanical Postbuckling of Composite Panels
Ahmed K. Noor

Three recent developments in the sensitivity analysis for the thermomechanical postbuckling response of composite panels are reviewed. The three developments are: effective computational procedure for evaluating hierarchical sensitivity coefficients of the various response quantities with respect to the different laminate, layer and micromechanical characteristics; application of reduction methods to the sensitivity analysis of the postbuckling response; and accurate evaluation of the sensitivity coefficients of transverse shear stresses. Sample numerical results are presented to demonstrate the effectiveness of the computational procedure presented. Some of the future directions for research on sensitivity analysis for the thermomechanical postbuckling response of composite and smart structures are outlined.
Aerospace Thermal Structures and Materials for a New Era, E. A. Thornton (ed.), AIAA Series Progress in Astronautics and Aeronautics, Vol. 168, 1995, pp. 218-239; also ASCE Journal of Engineering Mechanics, Vol. 122, No. 4, April 1996, pp. 300-307.

Three-Dimensional Analytical Solutions for Coupled Thermoelectroelastic Response of Multilayered Cylindrical Shells
Kangming Xu and Ahmed K. Noor

Analytical three-dimensional solutions are presented for the coupled thermoelectroelastic response of multilayered hybrid composite cylindrical shells. The shells consist of a combination of fiber-reinforced cross-ply and thermoelectroelastic layers. Both the thermoelectroelastic static response and its sensitivity coefficients are evaluated. The sensitivity coefficients measure the sensitivity of the response to variations in the different mechanical, thermal and piezoelectric material properties of the shells. A linear constitutive model is used, and the material properties are assumed to be independent of the temperature and the electric field. A mixed formulation is used with the fundamental unknowns consisting of the three transverse stress components; the three displacement components; the transverse component of the electric displacement field; the electric potential; the transverse heat-flux component; and the temperature change. Each of the fundamental unknowns is expressed in terms of a double Fourier series in the surface coordinates. A state-space approach is used to generate the static response and to evaluate the sensitivity coefficients. The response and sensitivity coefficients of the shell are obtained by using a modified Frobenius method and a sublayer method. Numerical results are presented

showing the effects of variation in the geometric parameters of the shells on the different response quantities and their sensitivity coefficients.
AIAA Journal, Vol. 34, No. 4, April 1996, pp. 802-812.

Sensitivity Analysis for the Dynamic Response of Thermoviscoplastic Shells of Revolution
Makarand Kulkarni and Ahmed K. Noor

A computational procedure is presented for evaluating the sensitivity coefficients of the dynamic axisymmetric, fully-coupled, thermoviscoplastic response of shells of revolution. The analytical formulation is based on Reissner's large deformation shell theory with the effects of large-strain, transverse shear deformation, rotatory inertia and moments turning around the normal to the middle surface included. The material model is chosen to be viscoplasticity with strain hardening and thermal hardening, and an associated flow rule is used with a von Mises effective stress. A mixed formulation is used for the shell equations with the fundamental unknowns consisting of six stress resultants, three generalized displacements and three velocity components. The energy-balance equation is solved using a Galerkin procedure, with the temperature as the fundamental unknown.

Spatial discretization is performed in one dimension (meridional direction) for the momentum and constitutive equations of the shell, and in two dimensions (meridional and thickness directions) for the energy-balance equation. The temporal integration is performed by using an explicit central difference scheme (leap-frog method) for the momentum equation; a predictor-corrector version of the trapezoidal rule is used for the energy-balance equation; and an explicit scheme consistent with the central difference method is used to integrate the constitutive equations. The sensitivity coefficients are evaluated by using a direct differentiation approach. Numerical results are presented for a spherical cap subjected to step loading. The sensitivity coefficients are generated by evaluating the derivatives of the response quantities with respect to the thickness, mass density, Young's modulus, two of the material parameters characterizing the viscoplastic response, and the three parameters characterizing the thermal response. Time histories of the response and sensitivity coefficients are presented, along with spatial discretization of some of these quantities at selected times.
Computer Methods in Applied Mechanics and Engineering, Vol. 129, 1996, pp. 371-391.

Sensitivity Analysis for Large Deflection and Postbuckling Responses on Distributed-Memory Computers
Brian C. Watson and Ahmed K. Noor

A computational strategy is presented for calculating sensitivity coefficients for the nonlinear large-deflection and postbuckling responses of laminated composite structures on distributed-memory parallel computers. The hierarchical sensitivity coefficients measure the sensitivity of the composite structure response to variations in three sets of interrelated parameters; namely, laminate, layer and micromechanical (fiber, matrix, and interface/interphase) parameters. The strategy is applicable to any message-passing distributed computational environment. The key elements of the proposed strategy are: a) a hierarchical sensitivity analysis procedure; b) a multiple-parameter reduced basis technique; c) a parallel sparse equation solver based on a nested dissection (or multilevel substructuring) node ordering scheme; and d) exploitation of parallelism at multiple levels within the analysis. The effectiveness of the strategy is assessed by performing hierarchical sensitivity analysis for the large-deflection and postbuckling responses of stiffened composite panels with cutouts on three distributed-memory computers. The

panels are subjected to combined mechanical and thermal loads. The numerical studies presented demonstrate the advantages of the reduced basis technique for sensitivity hierarchical analysis on distributed-memory machines.
Computer Methods in Applied Mechanics and Engineering, Vol. 129, 1996, pp. 393-409.

Computational Strategies for Tire Modeling and Analysis
Kent T. Danielson, Ahmed K. Noor and James S. Green

Computational strategies are presented for the modeling and analysis of tires in contact with pavement. A procedure is introduced for simple and accurate determination of tire cross-sectional geometric characteristics from a digitally scanned image. Three new strategies for reducing the computational effort in the finite element solution of tire-pavement contact are also presented. These strategies take advantage of the observation that footprint loads do not usually stimulate a significant tire response away from the pavement contact region. The finite element strategies differ in their level of approximation and required amount of computer resources. The effectiveness of the strategies is demonstrated by numerical examples of frictionless and frictional contact of the space shuttle Orbiter nose-gear tire. Both an in-house research code and a commercial finite element code are used in the numerical studies.
Computers and Structures (to appear).

Finite Elements Developed in Cylindrical Coordinates for Three-Dimensional Tire Analysis
Kent T. Danielson and Ahmed K. Noor

Finite elements developed in cylindrical coordinates are presented for three-dimensional analysis of tires. In contrast to elements formulated in Cartesian coordinates, these elements allow the exact representation of circular shapes. The exact modeling of circular geometries can provide better finite element predictions and reduce the number of elements needed around the tire circumference. Numerical results are presented for the application of this formulation to the analysis of a radial passenger tire subjected to rim mounting, nonconservative inflation pressure, and rigid pavement contact. The predictions of the foregoing finite elements are compared to experimental data and to predictions of a commercial code using finite elements developed in Cartesian coordinates. The comparisons demonstrate the accuracy and the advantages of the cylindrical coordinate formulation for three-dimensional finite element analysis of tires.
Tire Science and Technology (to appear).

Frictional Contact/Impact Response of Textile Composite Structures
Levent Karaoglan, Ahmed K. Noor and Yong H. Kim

The results of a detailed study of the frictional contact/impact response of axisymmetric textile composite structures are presented. The structures are assumed to consist of an arbitrary number of perfectly bonded layers of woven fabric or braided preforms. The material of each layer is assumed to be hyperelastic and the effect of geometric nonlinearity is included. The equations of motion of the structure are established in the current configuration and a displacement finite element model is used for the spatial discretization. A Coulomb friction model is used and the temporal integration is performed by using an explicit central difference scheme.

Both the dynamic response and the sensitivity coefficients are evaluated. The sensitivity coefficients measure the sensitivity of the response to variations in the effective layer properties. Numerical results are presented for the frictional contact/impact response of a spherical cap made of textile (woven and braided) composite material, impacting a rigid surface. Results are compared with those of a spherical cap made of tape laminate.
Composite Structures (to appear).

Assessment of Temporal Integration Schemes for the Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures
L. Karaoglan and A. K. Noor

An assessment is made of three temporal integration schemes for the sensitivity analysis of the frictional contact/impact response of axisymmetric composite structures. The structures considered consist of an arbitrary number of perfectly-bonded homogeneous anisotropic layers. The material of each layer is assumed to be hyperelastic, and the effect of geometric nonlinearity is included. Sensitivity coefficients measure the sensitivity of the response to variations in the different material, lamination and geometric parameters of the structure.

A displacement finite element model is used for the spatial discretization. Normal contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with fundamental unknowns consisting of both the nodal displacements and the Lagrange multipliers associated with the contact conditions. The Lagrange multipliers are allowed to be discontinuous at interelement boundaries. Tangential contact conditions are incorporated by using either a penalty method or a Lagrange multiplier technique, in conjunction with the classical Coulomb's friction model. The three temporal integration schemes considered are: the implicit Newmark and Houbolt schemes, and the explicit central difference method. In the case of the implicit methods, the Newton-Raphson iterative technique is used for the solution of the resulting nonlinear algebraic equations, and for the determination of the contact region, contact conditions (sliding or sticking), and the contact pressures. Sensitivity coefficients are evaluated by using a direct differentiation approach in conjunction with the incremental equations. Numerical results are presented for the frictional contact of a composite spherical cap impacting a rigid plate, showing the effects of each of the following factors on the accuracy of the predicted response and sensitivity coefficients: (a) incorporating the normal contact conditions, (b) the magnitude of the penalty parameter in the normal direction (for the perturbed Lagrangian method), and (c) the time step size for the response and the sensitivity analyses.
Computer Methods in Applied Mechanics and Engineering (to appear).

Buckling and Postbuckling of Composite Panels with Cutouts Subjected to Combined Loads
Yong H. Kim and Ahmed K. Noor

A detailed study is made of the buckling and postbuckling responses of composite panels with central circular cutouts subjected to various combinations of mechanical and thermal loads. The panels are discretized by using a two-field degenerate solid element with each of the displacement components having a linear variation through the thickness of the panel. The fundamental unknowns consist of the average mechanical strains through the thickness, and the displacement components. The effects of geometric nonlinearities and laminated anisotropic material behavior are included.

The stability boundary, postbuckling response and the hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the

buckling and postbuckling responses to variations in the panel stiffnesses, and the material properties of both the individual layers and the constituents (fibers and matrix). Extensive numerical results are presented for composite panels with central circular cutouts subjected to combined edge shortening, edge shear and temperature change. The results show the effects of variations in the hole diameter; the aspect ratio of the panel; the laminate stacking sequence and the fiber orientation on the stability boundary, postbuckling response and sensitivity coefficients.
Finite Elements in Analysis and Design (to appear).

Buckling and Postbuckling of Composite Panels with Cutouts Subjected to Combined Edge Shear and Temperature Change
Ahmed K. Noor and Yong H. Kim

The results of a detailed study of the buckling and postbuckling responses of composite panels with central circular cutouts are presented. The panels are subjected to combined edge shear and temperature change. The panels are discretized by using a two-field degenerate solid element with each of the displacement components having a linear variation throughout the thickness of the panel. The fundamental unknowns consist of the average mechanical strains through the thickness and the displacement components. The effects of geometric nonlinearities and laminated anisotropic material behavior are included.

The stability boundary, postbuckling response and the hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in the panel stiffnesses, and the material properties of both the individual layers and the constituents (fibers and matrix). Numerical results are presented for composite panels with central circular cutouts subjected to combined edge shear and temperature change, showing the effects of variations in the hole diameter, laminate stacking sequence and fiber orientation, on the stability boundary and postbuckling response and their sensitivity to changes in the various panel parameters.
Computers and Structures (to appear).

Reduction Technique for Tire Contact Problems
Ahmed K. Noor and Jeanne M. Peters

A reduction technique and a computational procedure are presented for predicting the tire contact response and evaluating the sensitivity coefficients of the different response quantities. The sensitivity coefficients measure the sensitivity of the contact response to variations in the geometric and material parameters of the tire. The tire is modeled using a two-dimensional laminated anisotropic shell theory with the effects of variation in geometric and material parameters, transverse shear deformation, and geometric nonlinearities included. The contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with the fundamental unknowns consisting of the stress resultants, the generalized displacements, and the Lagrange multipliers associated with the contact conditions. The elemental arrays are obtained by using a modified two-field, mixed variational principle.

For the application of the reduction technique, the tire finite element model is partitioned into two regions. The first region consists of the nodes that are likely to come in contact with the pavement, and the second region includes all the remaining nodes. The reduction technique is used to significantly reduce the degrees of freedom in the second region.

The effectiveness of the computational procedure is demonstrated by a numerical example of the frictionless contact response of the space shuttle nose-gear tire, inflated and pressed against a rigid flat surface.
In NASA CP-3306, pp. 69-88; also Computers and Structures (to appear).

Nonlinear and Postbuckling Analyses of Curved Composite Panels Subjected to Combined Temperature Change and Edge Shear
Ahmed K. Noor and Jeanne M. Peters

The results of a detailed study of the nonlinear and postbuckling responses of curved unstiffened composite panels with central circular cutouts are presented. The panels are subjected to uniform temperature change and an applied in-plane edge shear loading. The analysis is based on a first-order shear-deformation Sanders-Budiansky type theory with the effects of large displacements, moderate rotations, transverse shear deformation and laminated anisotropic material behavior included. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated.

Numerical results are presented for cylindrical panels with central circular cutouts and subjected to uniform temperature change and an applied in-plane edge shear loading. The results show the effects of variations in the panel curvature, hole diameter, laminate stacking sequence and fiber orientation, on the nonlinear and postbuckling panel responses, and their sensitivity to changes in the various panel, layer and micromechanical parameters.
Computers and Structures (to appear).

Sensitivity Analysis of the Contact/Impact Response of Composite Structures
Gerry D. Pollock and Ahmed K. Noor

A computational strategy is presented for evaluating the sensitivity coefficients of the contact-impact response of composite shell structures. A total Lagrangian description is used for the geometrically nonlinear continuum equations. Shells with an arbitrary number of perfectly bonded, hyperelastic, anisotropic layers are considered. The spatial discretization is performed by using a higher-order, quasi-three-dimensional, two-field mixed finite element model with the fundamental unknowns consisting of strain and displacement components. The equations of motion are integrated using an explicit central-difference scheme. Coulomb's friction law, incorporating static and dynamic coefficients of friction, is used to model the frictional response. The conditions of frictional and normal contact between the shell and a rigid planar surface are enforced using the Lagrange multiplier technique. The sensitivity coefficients, which are evaluated using a direct differentiation approach, measure the sensitivity of the response to variations in the material properties and the coefficient of friction. Numerical results are presented for the frictional contact/impact response and sensitivity coefficients of inclined cylinders impacting a rigid plate.
Computers and Structures (to appear).

A Hybrid Numerical/Neurocomputing Strategy for Sensitivity Analysis of Nonlinear Structures
Z. Peter Szewczyk and Ahmed K. Noor

A hybrid numerical/neurocomputing (HN/N) strategy is presented for the evaluation of selective sensitivity coefficients of nonlinear structures. In the hybrid strategy, multilayer feedforward neural networks are used to extend a range of the validity of predictions of sensitivity coefficients made by Pade' approximants. To further increase the accuracy and the range of network predictions, a data expansion strategy is used in which additional training data are generated by using extrapolated values of the coefficients in a Taylor series. Within this strategy a number of techniques are examined for evaluating derivatives of response functions. The effectiveness of the HN/N strategy is assessed by performing numerical experiments for composite panels subjected to combined thermal and mechanical loads. It is shown that the HN/N strategy reduces the number of full-system analyses and allows obtaining selective information about the structural response and the sensitivity coefficients.
Computers and Structures (to appear).

Assessment of Computational Models for Thermoelectroelastic Multilayered Plates
Yvette Y. Tang, Ahmed K. Noor and Kangming Xu

A study is made of the accuracy of the steady-state (static) thermoelectroelastic response of multilayered hybrid composite plates predicted by five modeling approaches, based on two-dimensional plate theories. The plates consist of a combination of fiber-reinforced and piezothermoelastic layers. The standard of comparison is taken to be the exact three-dimensional thermoelectroelastic solutions, and the quantities compared include gross response characteristics (e.g. strain energy components, and average through-the-thickness displacements); detailed, through-the-thickness distributions of displacements and stresses; and sensitivity coefficients of the response quantities (derivatives of the response quantities with respect to material parameters of the plate).

The modeling approaches considered include first-order theory; third-order theory; discrete-layer theory (with piecewise linear variation of the in-plane displacements, temperature and electric potential, in the thickness direction); and two predictor-corrector procedures. Both procedures use first-order theory in the predictor phase, but differ in the elements of the computational model being adjusted in the corrector phase. The first procedure adjusts the transverse shear stiffnesses of the plate and the second procedure corrects the functional dependence of the displacements on the thickness coordinate. The corrected quantities are then used in conjunction with the three-dimensional equations to obtain better estimates for the different response quantities and their sensitivity coefficients.

Numerical results are presented for nine-layer plates consisting of eight graphite-epoxy layers and one piezothermoelastic layer, subjected to transverse mechanical loading, temperature change and electric potential. Based on the numerical studies conducted, the second predictor-corrector approach appears to be the most accurate among the five modeling approaches considered. For multilayered hybrid composite plates, the detailed response quantities, and sensitivity coefficients obtained by this approach are shown to be in close agreement with the exact three-dimensional thermoelectroelastic solutions for a wide range of the thickness parameter.
Computers and Structures (to appear).

Modeling and Sensitivity Analysis of Multibody Systems Using New Solid, Shell and Beam Elements
Tamer M. Wasfy and Ahmed K. Noor

A computational procedure is presented for predicting the dynamic response and evaluating the sensitivity coefficients of large, flexible multibody systems consisting of beams, shells and solids undergoing arbitrary spatial motions. The sensitivity coefficients measure the sensitivity of the dynamic response to variations in the material, geometric and external force parameters of the system. The four key elements of the procedure are: a) new beam, shell and solid elements with the Cartesian coordinates selected as degrees of freedom and with continuous inter-element slopes; b) a corotational frame approach in conjunction with a total Lagrangian formulation; c) semi-explicit temporal integration for generating the dynamic response; and d) direct differentiation approach for evaluating the sensitivity coefficients. The nonlinear interactions between the elastic and the large rigid body motion are naturally incorporated in the present formulation. The effectiveness of the procedure is demonstrated through numerical examples including an articulated space structure consisting of beams, shells and revolute joints.
Computer Methods in Applied Mechanics and Engineering (to appear).

Sensitivity Analysis of Frictional Contact/Impact Response on Distributed-Memory Computers
Brian C. Watson and Ahmed K. Noor

Multilevel parallel computational strategies are presented for predicting the frictional contact/impact response and evaluating the sensitivity coefficients of axisymmetric composite structures. Both implicit and explicit temporal integration techniques are considered. For implicit techniques, parallelism is exploited in both the spatial and temporal domains. Spatial parallelism is achieved by using a parallel sparse equation solver based on a nested dissection node-ordering scheme. The explicit techniques exploit parallelism using both an element-based domain decomposition strategy, as well as concurrent evaluation of sensitivity coefficients. Implementations of the strategies on distributed-memory computers are described. The strategies are applied to the problem of an axisymmetric composite spherical cap impacting a rigid surface, and the performance characteristics are assessed on the IBM SP2 and the Cray T3D parallel computer systems.
Computers and Structures (to appear).

Large-Scale Contact/Impact Simulation and Sensitivity Analysis on Distributed-Memory Computers
Brian C. Watson and Ahmed K. Noor

A parallel computational strategy is presented for simulating frictional contact/impact response and evaluating sensitivity coefficients for large-scale finite element models of composite structures. The explicit central difference scheme is used for the temporal integration of the semi-discrete governing equations. The two key elements of the strategy are: (a) an element-based domain decomposition technique; and (b) a robust exchange algorithm for communicating information across subdomain interfaces. An implementation of the strategy suitable for any distributed-memory computing system (including clusters of workstations) is described. Numerical results are presented for three structures impacting a rigid surface. The three structures are: an inclined composite cylinder, an inclined stiffened cylinder, and an Advanced Composites Technology (ACT) program test panel. For each of these problems, the performance characteristics of the computational procedure are assessed on the IBM SP2 parallel computer system.
Computer Methods in Applied Mechanics and Engineering (to appear).

Three-Dimensional Solutions for Free Vibrations of Initially-Stressed Thermoelectroelastic Multilayered Cylinders
Kangming Xu, Ahmed K. Noor and W. Scott Burton

Analytic three-dimensional solutions are presented for the free vibration problems of initially stressed hybrid multilayered composite circular cylindrical shells. The shells consist of a combination of fiber-reinforced cross-ply and piezothermoelastic layers. The initial stresses are generated by either a temperature change and/or an electric field. Sensitivity coefficients are also evaluated and used to study the sensitivity of the vibrational response to variations in the different mechanical, thermal and piezoelectric material properties of the shells. Both the temperature change and the radial component of the electric field are assumed to have uniform distribution in each layer of the shells. A linear constitutive model is used, and the material properties are assumed to be independent of both the temperature and the electric field. The thermoelectroelastic response of the shell is subjected to time-varying displacements, strains and stresses, and the free vibration response is studied.

A mixed formulation is used with the fundamental unknowns consisting of the increments of the three transverse stress components and the three displacement components of the shell. Each of the fundamental unknowns is expressed in terms of a double Fourier series in the axial and circumferential surface coordinates. A state space approach is used to generate the vibrational response and to evaluate the sensitivity coefficients. A sublayer method is used for evaluating vibration frequencies and their sensitivity coefficients. Numerical results are presented showing the effects of variation in the shell thickness, and the location of the piezothermoelastic layers on the vibration frequencies and their sensitivity coefficients.
Journal of Engineering Mechanics, ASCE (to appear).

Three-Dimensional Solutions for Free Vibrations of Initially-Stressed Thermoelectroelastic Multilayered Plates
Kangming Xu, Ahmed K. Noor and Yvette Y. Tang

Analytic three-dimensional solutions are presented for the free vibration frequencies of initially stressed hybrid multilayered composite plates. The plates consist of a combination of fiber-reinforced cross-ply and piezothermoelastic layers. The initial stresses are generated by either a temperature change and/or an electric field. Sensitivity coefficients are also evaluated and used to study the sensitivity of the vibrational response to variations in the different mechanical, thermal and piezoelectric material properties of the plate. Both the temperature change and the electric field are assumed to be independent of the surface coordinates, but have arbitrary variation through the thickness of the plate. A linear constitutive model is used, and the material properties are assumed to be independent of both the temperature and the electric field. The thermoelectroelastic response of the plate is subjected to time-varying displacements, strains and stresses.

A mixed formulation is used with the fundamental unknowns consisting of the three increments of the transverse stress components and the three displacement components. Each of the fundamental unknowns is expressed in terms of a double Fourier series in the Cartesian surface coordinates. A state space approach is used to generate the vibrational response and to evaluate the sensitivity coefficients. Approximate and closed-formed expressions are developed relating the vibration frequency for the initially-stressed plate to the corresponding frequency of the unstressed plate. A nonlinear eigen-derivative theory is applied to obtain the sensitivity coefficients of the vibration frequency of the plate. Approximate expressions for the sensitivity coefficients are also derived. Extensive

numerical results are presented showing the effects of variation in the plate thickness and the location of the piezothermoelastic layers on the vibration frequencies and their sensitivity coefficients.
Computer Methods in Applied Mechanics and Engineering (to appear).

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